Ecological Indicators 101 (2019) 261–273

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

Changes in wetlands and surrounding land cover in a desert area under the influences of human and climatic factors: A case study of the Hongjian Nur region

Lina Xiu[a,b], Changzhen Yan[a,*], Xiaosong Li[c], Dawen Qian[d], Kun Feng[a,b]

[a] Key Laboratory of Desert and Desertification, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou, PR China
[b] University of Chinese Academy of Sciences, Beijing 100049, PR China
[c] Institute of Remote Sensing and Digital Earth Chinese Academy of Sciences, Beijing 100101, PR China
[d] Northwest Institute of Plateau Biology, Chinese Academy of Sciences, Xining, PR China

ARTICLE INFO

Keywords:
Cultivated land change
Vegetation change
NDVI
Ecological restoration projects

ABSTRACT

Wetlands, as the transition zones between land and aquatic systems, are one of nature's most biologically diverse ecosystem types and are important environments for humans. In arid deserts, the roles of wetlands are particularly important. The Hongjian Nur region (HJN), which has the largest desert freshwater lake in China, is not only a national reserve but also the largest breeding ground for *Larus relictus* in the world. However, due to climate change and human activities, extensive wetland changes have occurred in the HJN region in recent decades. To investigate the changes of wetlands in the HJN region, the dynamics of wetlands and surrounding land cover types in this region over the past three decades were studied using remote sensing. In addition, how these dynamics have been affected by climatic and human factors was analyzed. The results suggested that the area of wetlands presented a decreasing trend over the studied time period from 62.54 km^2 to 35.89 km^2, with an average rate of change of -0.66 km^2/year. The reduction in wetland area was mainly caused by climatic and human factors. The contribution of temperature and precipitation to vegetation growth were small, and the impacts of human activities on the wetland areas of the HJN region were mainly caused by agricultural irrigation, artificial surface expansion and ecological water use. The results also suggested that human activities in arid regions may have negative impacts on fragile wetland ecosystems.

1. Introduction

Wetlands are recognized as important ecosystems, and they often provide critical ecosystem functions, such as flood reduction, fish production, carbon storage, and conservation of biological diversity (Han et al., 2014; Zhang et al., 2016). Specific hydrological conditions drive the formation and maintenance of wetlands, and this dependence is particularly evident in arid regions (Moreno-Mateos et al., 2010; Halabisky et al., 2016; Maleki et al., 2016). The Hongjian Nur (HJN) region, which is located in the marginal area of the Mu Us Sandy Land, has the largest desert freshwater lake in China, known as the Desert Pearl (Luo et al., 2012; Yu et al., 2016). The HJN region is not only a national reserve but also the largest breeding ground for *Larus relictus* in the world. The wetlands in the HJN region play important roles in regulating the local climate and water resources and in maintaining biological diversity (Li et al., 2009b; Deng et al., 2014; Yang et al., 2014; Xiang et al., 2016). The geographical location of the HJN region makes it vulnerable to climatic and human influences (Liu et al., 2015a, 2017; Zhao et al., 2016). Due to climate change and human activities, extensive changes in wetlands have occurred over recent decades, degrading their ecological functions and generating numerous environmental and social problems (Fensham et al., 2011; Glenn et al., 2013; Han et al., 2014). Thus, monitoring and understanding wetland changes are important to both the scientific community and the local governments.

In previous decades, many efforts have been devoted to monitoring the wetlands in the HJN region (Wang et al., 2011; Xiang et al., 2016; Yu et al., 2016; Zhao et al., 2016). Wang et al. (2011) used Landsat satellite remote sensing data to monitor the dynamic changes in the lake area of the HJN region over a 36-year period. The results demonstrated that the lake area decreased by 19.7 km^2 between 1973 and 2009, with a stronger decreasing trend after 2000. Yu et al. (2016) conducted heavy metal analyses of the surface sediments of wetlands in the HJN region, and identified slight heavy metal pollution in the

* Corresponding author.
E-mail address: yancz@lzb.ac.cn (C. Yan).

https://doi.org/10.1016/j.ecolind.2019.01.025
Received 11 May 2018; Received in revised form 9 October 2018; Accepted 9 January 2019
Available online 16 January 2019
1470-160X/ © 2019 Elsevier Ltd. All rights reserved.

region, with a low potential ecological risk index. Xiang et al. (2016) analyzed the relationships between *Larus relictus* populations and their habitat sensitivity in the HJN wetlands from 2001 to 2011. They found that there had been an increase in the area of forestland and that the degree of sandy land and the fragmentation of grassland were the key factors affecting the sustainability and steady growth of the *Larus relictus* populations. Zhao et al. (2016) found that climate warming and drying were the main factors affecting the wetlands of the HJN region during the stable period (i.e., 1973–1994); furthermore, human activities and the warm and dry climate contributed to the decrease in wetland area during the period of reduction (i.e., 1994–2013). These studies indicate that the wetland area in this region has been decreasing and that the quality of the lake water has been deteriorating. As a result, the population size of *Larus relictus* has been affected. However, many studies have demonstrated that the vegetation conditions around wetland areas have improved in association with a series of ecological projects implemented in China (Li et al., 2010; Zhang et al., 2011; Liu et al., 2017).

Wetlands are important ecosystems that produce numerous beneficial services (Trenholm et al., 2017), and they play important roles in affecting surrounding land cover types, especially in arid regions. However, changes in land cover type around wetlands may cause problems, such lowered groundwater levels, with negative impacts on wetlands (Sultan et al., 2004; Fu and Burgher, 2015; Zhu et al., 2015). For example, research in the Loess Plateau demonstrated that vegetation restoration projects improved vegetation growth but potentially had negative impacts on local water resources (Liu et al., 2018). In arid or desert regions, the negative impacts of human activities on wetlands remain unclear. Therefore, further analyses of the relationships between wetlands and their surrounding land cover types are needed. In this study, we investigated the dynamics of wetlands and surrounding land cover types in the HJN region over the past three decades using a remote sensing technique. The relationships between these dynamics and temperature and precipitation were analyzed, and the impacts of human activities on wetland changes were investigated.

2. Study area

The HJN region (38°52′–39°20′ N, 109°30′–110°06′ E) is located at the junction of Shenmu County of Shaanxi Province and Ejin Horo of Inner Mongolia, and the region covers an area of 1493.24 km^2 (Fig. 1). The HJN region is situated at the transitional zone between the Loess Plateau and the Inner Mongolia Plateau and at the intersection between the Mu Us Sandy Land and the Ordos Basin. The average elevation is 1200 m. The study area belongs to the temperate semiarid continental monsoon climate, which is characterized by dry and windy conditions and clear seasons. The average annual temperature is 9.5 °C, and the average annual rainfall is 400 mm and is unevenly distributed throughout the year. Precipitation is mainly concentrated from July to September. However, the average annual evaporation in the entire basin is 1200 mm. HJN Lake is the largest lake in the region, and seven seasonal rivers flow into the lake. Most of the area around the lake consists of fixed sand dunes and desertified hills. The vegetation is typical sandy vegetation, including *Nitraria tangutorum, Artemisia ordosica,* and *Salix cheilophila*. More than thirty species of wild rare birds frequent the region, including *Larus relictus, Ciconia nigra* and *Aquila chrysaetos* (Zhao et al., 2016).

3. Materials and methods

3.1. NDVI data sources and preprocessing

The remote sensing datasets used in this study included the normalized difference vegetation index (NDVI) datasets from NOAA/AVHRR and TERRA/AQUA MODIS. The NOAA/AVHRR NDVI dataset was generated from the global inventory modeling and mapping studies (GIMMS) of the Goddard Space Flight Center (GSFC) with a spatial resolution of 8 km × 8 km, a 15-day temporal resolution, and an Albers conic projection in 32-bit GeoTIFF format from January 1982 to December 2006 (ftp.glcf.umiacs.umd.edu). The data were preprocessed for geometric correction, radiometric correction, and atmospheric correction; additionally, the maximum value composite (MVC) was used to reduce the effects of cloud, atmosphere, and solar elevation angles (Holben, 1986). MOD13A3 is the monthly vegetation index product developed by the MODIS Terrestrial Product Group. It includes the MVC NDVI and enhanced vegetation index (EVI) with a spatial resolution of 1 km × 1 km and can be accessed through the NASA Earth Observation System Data Sharing platform (https://earthdata.nasa.gov/). For this study, the data from 2000 to 2015 were downloaded.

A previous study found a large difference between the GIMMS and GIMMS 3 g datasets in the northern hemisphere and suggested that GIMMS and MODIS can be used in conjunction (Guay et al., 2014). The time series of NDVI data can be extended using the correlation between the GIMMS NDVI and the MODIS NDVI. Here, monthly GIMMS NDVI data were generated using the MVC method via the 15-day NDVI dataset, and then the monthly NDVI dataset of GIMMS was resampled based on the MODIS 1-km grid. This study selected NDVI as an indicator to study the status of vegetation. In general, areas where NDVI ≤ 0 are nonvegetated regions. To eliminate the effects of no vegetation, the grid values with NDVI > 0 in each month were selected to calculate the linear correlation coefficient (Table 1) between the GIMMS NDVI and the MODIS NDVI in China from 2000 to 2006. Finally, based on this relationship, the time series of the MODIS NDVI was extended by using the GIMMS monthly NDVI from 1982 to 1999 (Xin et al., 2008; Mao et al., 2012; Xu et al., 2016).

3.2. Meteorological data sources and preprocessing

The meteorological data were derived from the China Meteorological Science Data Sharing Service Network (http://cdc.cma.gov.cn/home.do), and included the daily mean temperature and precipitation for the HJN region and its surrounding areas from 1982 to 2015. We used the ANUSPLIN software package version 4.3 (Hutchinson and Xu, 2013), which implements the thin-plate smoothing splines procedure described by Hutchinson (Hutchinson, 1995; Hijmans et al., 2005). We chose this method because it has been widely used in spatial interpolation analyses of climate elements (Liu et al., 2016; Mandal et al., 2016) and performs well in comparison with other methods, such as inverse distance weighted (IDW) and kriging (Jiang et al., 2010).

3.3. Land cover classification

The satellite images used for land cover analysis in the study area included a cloud-free Landsat MSS image from 1976, TM images from 1990/1995/2000/2005/2010 and OLI images from 2015, which were downloaded from the USGS website (http://glovis.usgs.gov/). Information on the satellite data used are provided in Table 2. Most of the selected images were obtained from June to September, and missing images or images of poor quality were replaced with images from the closest month or year during this period. The selected timeframe selected can minimize the errors caused by seasonal fluctuations in wetland area, thereby ensuring the consistency of different image phases. The period of June to September also corresponds to the period of seasonal vegetation growth around the wetland. Before we extracted the land cover information, the images were preprocessed by geometric correction, radiometric correction, and atmospheric correction. Seven different land cover types were identified: woodland, grassland, sparse vegetation, wetland, cultivated land, artificial surface and non-used land (Zhang et al., 2014). Wetland included rivers, lakes, irrigation reservoirs and ponds. The land cover information was extracted from the images by using eCognition 8.6 software, which uses an object-

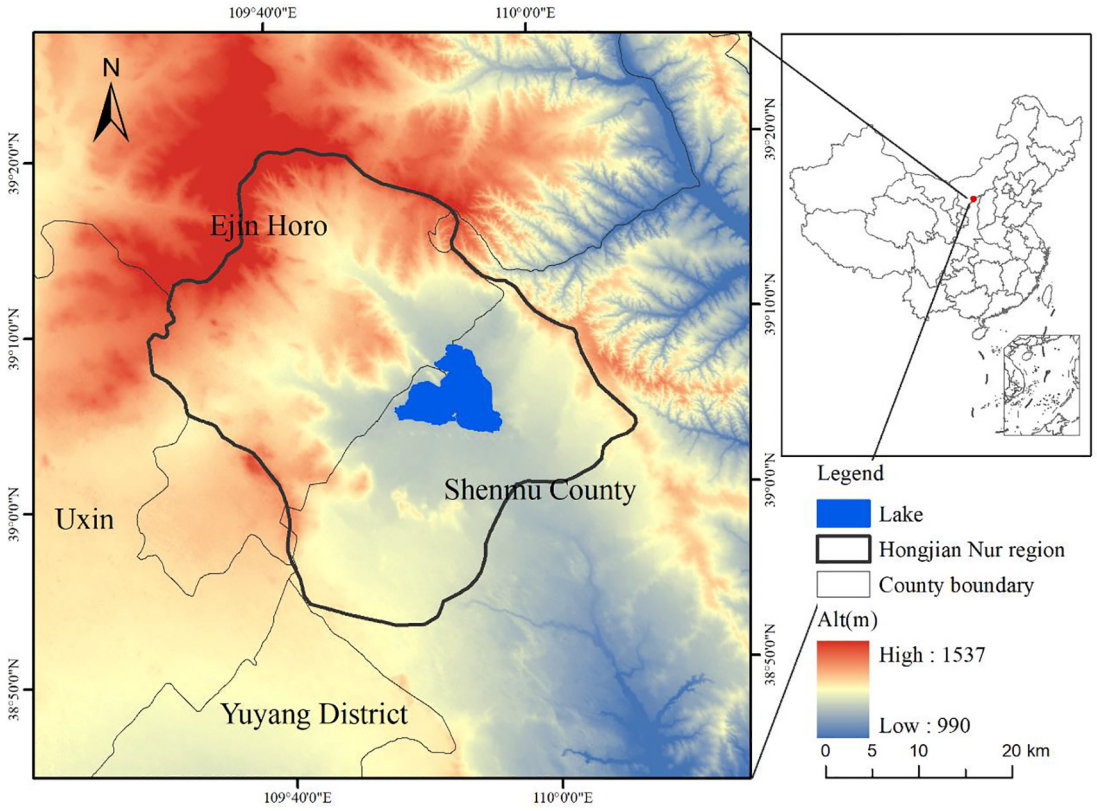

Fig. 1. The location of the HJN region in China.

Table 1
The correlation between the GIMMS NDVI and the MODIS NDVI.

Month	N	Parameter estimation		Regression results	
		a	b	r^2	RMSE
January	226,985	0.727	0.033	0.845	0.051
February	222,175	0.749	0.023	0.873	0.042
March	335,459	0.709	0.030	0.838	0.045
April	370,184	0.781	0.020	0.875	0.048
May	376,391	0.824	0.013	0.873	0.064
June	391,512	0.849	0.010	0.852	0.083
July	421,885	0.888	0.007	0.881	0.087
August	424,014	0.883	0.010	0.877	0.089
September	413,307	0.855	0.019	0.872	0.080
October	373,024	0.792	0.024	0.879	0.056
November	322,274	0.792	0.017	0.915	0.042
December	307,161	0.752	0.020	0.874	0.047

Table 2
Satellite images used for land cover analysis in the study area.

Path/Row	Satellite sensor	Observation date
127/033	MSS	03/11/1976
	TM	09/11/1989
		11/15/1995
		07/31/2000
		09/10/2006
		06/30/2009
	OLI	07/01/2015

oriented classification approach (Hulet et al., 2014; Voltersen et al., 2014; Qian et al., 2017). The results of the land-use classifications in 2015 were evaluated for 400 sampling points. The results of the accuracy evaluation are shown in Table 3.

Table 3
Results of the land cover accuracy assessment in 2015.

Land cover	User accuracy (%)	Producer accuracy (%)
Vegetation	92.3	91.1
Wetland	100.0	98.7
Cultivated land	95.4	93.4
Artificial surface	100	100.0
Non-used land	95.6	93.8
Overall accuracy	96.5	–
Kappa statistic	95.7	–

3.4. Specific research methods

3.4.1. Linear regression method

A linear regression analysis can simulate the trend of each pixel over the past 34 years. Stow et al. (2003) used this method to calculate the greenness rate of change (GRC) of vegetation. GRC is defined as the slope of the minimum sublinear regression equation of the seasonally integrated normalized difference index (SINDVI) for a given period of time (Zhang et al., 2013). In this study, the method was used to simulate the trend of seasonal NDVI in the study area. The formula was as follows:

$$\theta_{slope} = \frac{n \times \sum_{i=1}^{n} i \times NDVI_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} NDVI_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2} \quad (1)$$

where n is the time series length of the simulation ($n = 34$), the variable i is the sequence number of the time series, and $NDVI_i$ is the average value of SINDVI in the i-th year. The numerical trend reflects the trend of annual NDVI during the study period. The trend line of a given point represents the general trend of the average NDVI value during the 34 years. $\theta_{slope} > 0$ indicates an increasing trend of NDVI, and $\theta_{slope} < 0$ indicates a decreasing trend of NDVI.

3.4.2. The cumulative departure from the mean

The cumulative departure from the mean (CDM) is a method used to analyze trends in time series data (Archer and Fowler, 2004; Yan et al., 2016). The CDM was calculated using the following formula:

$$\mathrm{CDM} = \sum_{i=1}^{n} (x_i - \bar{X})/\bar{X} \quad (2)$$

where n is the time series length (n = 34), the variable x_i is the annual temperature or precipitation in the i-th year, and $\bar{X}$ is the average of the annual temperature or precipitation from 1982 to 2015.

3.4.3. Population data

Due to the difficulty in obtaining historical population data for the HJN region, this study used the population data of Ejin Horo and Shenmu County to identify the demographic trends in the region. The population data of Ejin Horo come from the Inner Mongolia Statistical Yearbook (http://www.nmgtj.gov.cn/acmrdatashownmgpub/index.htm), and the Shenmu County population data come from the Shaanxi Yearbook (http://navi.cnki.net/knavi/YearbookDetail?pcode=CYFD&pykm=YPDMD).

4. Results

4.1. Changes in wetlands and surrounding land cover

The land cover changes in the HJN region obtained from Landsat images during 1976–2015 are shown in Table 4. The area of wetland presented a decreasing trend from 62.54 to 35.89 km^2, with an average rate of change of area was −0.66 km^2/year. From Fig. 2, it can be seen that the area of the lake decreased from 1976 to 2015. However, concurrently, the area of the irrigation reservoir increased. In 1976, the lake area began to decrease slowly, and this trend persisted until 2000, when the area of the lake decreased extensively. Since 2000, the irrigation reservoir area has increased rapidly. The types of land cover around the wetland have exhibited the following changes. The vegetation area widely fluctuated throughout the 40-year period. The largest area of vegetation was 1101.55 km^2 in 2000, and the smallest was 1076.26 km^2 in 2015. As shown in Table 4, the change in vegetation area can be divided into two periods (i.e., 1976–2000 and 2000–2015). During the first period (1976–2000), the area of vegetation exhibited an increasing trend; however, during the second period (2000–2015), the area of vegetation decreased. The area of woodland exhibited an increasing trend until 2005 and a decreasing trend thereafter. The area of sparse vegetation increased until 2010. In contrast, the area of grassland has consistently decreased. The areas of cultivated land and artificial surface displayed increasing trends, with average rates of increase of 1.14 km^2/year and 0.52 km^2/year, respectively. The area of non-used land, which comprised sandy land, saline land and bare land, had a decreasing trend before 1995; then, it presented a steady trend between 99.78 km^2 and 102.26 km^2 after 1995.

According to the change trends of the different land cover types in the HJN, the relationships among the various types of change in 1976–2000 and 2000–2015 were investigated (Tables 5, 6). By 2000, portions of the former wetland had been converted mainly into cultivated land, followed by grassland and sparse vegetation. These findings indicated that land reclamation led to a reduction in wetland area. During 2000–2015, the portions of wetland were mainly converted to grassland. The continuous expansion of cultivated land not only had a negative impact on the wetland area but also encroached on the area of growing vegetation. During the periods 1976–2000 and 2000–2015, the increase in woodland was mainly due to the conversion of grassland, with increases in woodland area of 2.504 km^2 and 0.543 km^2 in the first and second periods, respectively. The above results indicate that the increase in woodland was mainly driven by human activities due to the unique geographical environment of the region.

For the period 1976 to 2000, areas of sparse vegetation were mainly converted into grassland and cultivated land, with the area converted to grassland being larger, increasing by 4.691 km^2. The increased in sparse vegetation was mainly due to the reduction of wetland, exhibiting a change of 2.729 km^2. After 2000, portions of sparse vegetation were mainly converted to cultivated land, corresponding to a change of 4.924 km^2. The increased in sparse vegetation was mainly due to the conversion of grassland and wetland, corresponding to area changes of 4.357 km^2 and 1.293 km^2, respectively. The change in sparse vegetation indicated the increasing activity of human.

Before 2000, the vegetation conditions in the study area were gradually improved. As the area of wetland decreased, grassland degraded in some areas. The overall grassland area decreased. After 1976, areas converted from grassland primarily contained cultivated land and woodland, which exhibited increases of 14.979 km^2 and 2.504 km^2, respectively. The increased area was mainly from the transformation of sparse vegetation and wetland. After 2000, areas of converted grassland mainly represented cultivated land (15.278 km^2) and sparse vegetation (4.357 km^2). Formerly non-used land areas were mainly converted to vegetation areas. The above results indicate that human land reclamation exerted negative impacts on vegetation growth, whereas the vegetation restoration projects positively affected the vegetation of the region. In addition, the reduction in wetland area indirectly affected the growth of vegetation.

4.2. Temporal and spatial variations in NDVI

The annual NDVI presented an increasing trend over the past 34 years; for example, between 2001 and 2014, the NDVI increased from 0.205 to 0.324 (Fig. 3). The annual NDVI during 2000–2015 increased more than it did during 1982–1999; thus, the change in the annual NDVI was divided into two periods: an increasing period and a rapidly increasing period. The first period was from 1982 to 1999, in which the annual NDVI ranged from 0.207 to 0.300, with an average rate of change was 0.005. The second period was from 2000 to 2015, during which the annual NDVI increased from 0.205 to 0.324, and the average rate of change was 0.006 per year. To investigate the main vegetation differences between the two periods, the intra-annual vegetation variation was analyzed from 1982 to 2015 (Fig. 4). The results

Table 4
Land cover changes in the HJN region from 1976 to 2015 (km^2).

Year	Wetland	Woodland	Grassland	Sparse vegetation	Cultivated land	Artificial surface	Non-used land
1976	62.54	109.06	741.77	239.05	206.90	7.20	126.73
1990	61.02	110.23	732.67	240.79	214.85	7.21	126.46
1995	54.67	111.78	734.62	253.53	227.42	10.08	101.13
2000	47.89	112.00	732.28	257.28	231.85	9.69	102.26
2005	45.49	112.85	723.56	257.75	236.02	17.78	99.78
2010	43.40	112.60	717.98	260.99	236.82	19.77	101.67
2015	35.89	111.11	712.24	252.91	252.80	27.84	100.44

Note: Coal mines, a type of artificial surface, began to appear in 1995, with areas of 0.01 km^2, 0.03 km^2, 2.89 km^2, 2.99 km^2 and 4.41 km^2 in 1995, 2000, 2005, 2010 and 2015, respectively.

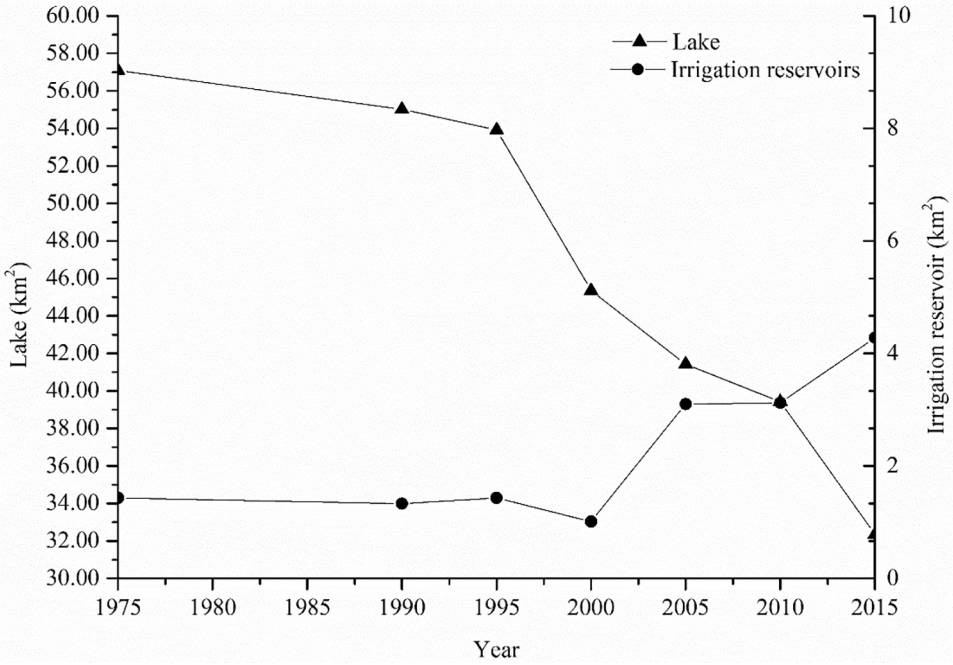

Fig. 2. Changes in the lake and irrigation reservoir areas from 1976 to 2015.

Table 5
The transfer matrix of land cover changes in the HJN region during 1976–2000 (km^2).

Type	Woodland	Grassland	Sparse vegetation	Wetland	Cultivated land	Artificial surface	Non-used land
Woodland	108.485	–	0.002	–	0.569	–	–
Grassland	2.504	719.795	0.992	1.802	14.979	1.703	–
Sparse vegetation	0.519	4.691	231.912	0.009	1.747	0.169	–
Wetland	0.384	4.807	2.729	47.097	7.438	0.009	1.509
Cultivated land	–	0.090	0.243	0.001	205.446	1.027	0.090
Artificial surface	–	–	–	–	–	5.767	–
Non-used land	0.108	2.892	21.398	–	1.669	–	100.662

Table 6
The transfer matrix of land cover changes in the HJN region during 2000–2015 (km^2).

Type	Woodland	Grassland	Sparse vegetation	Wetland	Cultivated land	Artificial surface	Non-used land
Woodland	110.567	0.002	–	0.060	0.493	0.730	0.147
Grassland	0.543	700.773	4.357	2.540	15.278	8.406	0.379
Sparse vegetation	0.000	0.847	246.435	–	4.924	5.069	–
Wetland	–	9.465	1.293	35.502	2.348	–	0.301
Cultivated land	–	1.123	0.028	0.100	229.762	0.544	0.290
Artificial surface	–	–	–	–	–	8.675	–
Non-used land	–	0.033	0.792	1.972	–	0.136	99.328

demonstrated that the growing season of vegetation in the study area was mainly concentrated from May to September, and the mean NDVI values of the vegetation growing seasons during 1982–1999 and 2000–2015 were 0.238 and 0.260, respectively, with the latter representing an increase of 9.03%. The highest NDVI value appeared in August. The highest NDVI values in the first and second periods were 0.286 and 0.320, respectively, with the latter representing an increase of 9.44%.

The spatial distribution of vegetation was further studied for the periods 1982–2015 and 2000–2015. From 1982 to 2015, the area with improved vegetation status accounted for 79.65% of the HJN region, and the improved area was slightly larger in Shenmu County of Shaanxi Province than that in Ejin Horo of the Inner Mongolia Autonomous Region (Fig. 5a). After 2000, the area of improved vegetation increased by 98.53% in the study area, and the area of improved vegetation in Ejin Horo was slightly larger than that in Shenmu County (Fig. 5b).

4.3. Relationships between wetlands and surrounding vegetation.

To maintain the time series consistency of the NDVI and land cover data, this study focused the changes in wetland area and the NDVI values of the surrounding vegetation after 1990. From 1990 to 2015, the wetland area decreased by 41.18%; after 2000, the annual average NDVI of vegetation around the wetland began to increase, reaching 22.48% by 2015 (Table 7). The area of wetlands in the HJN region decreased, and the NDVI value of the surrounding vegetation increased. Therefore, we next investigated the causes of these patterns.

4.4. The influence of climate change

The temporal change in average annual temperature and its cumulative departure curve from 1982 to 2015 are shown in Fig. 6. The average annual temperature exhibited an increasing trend from 1982 to

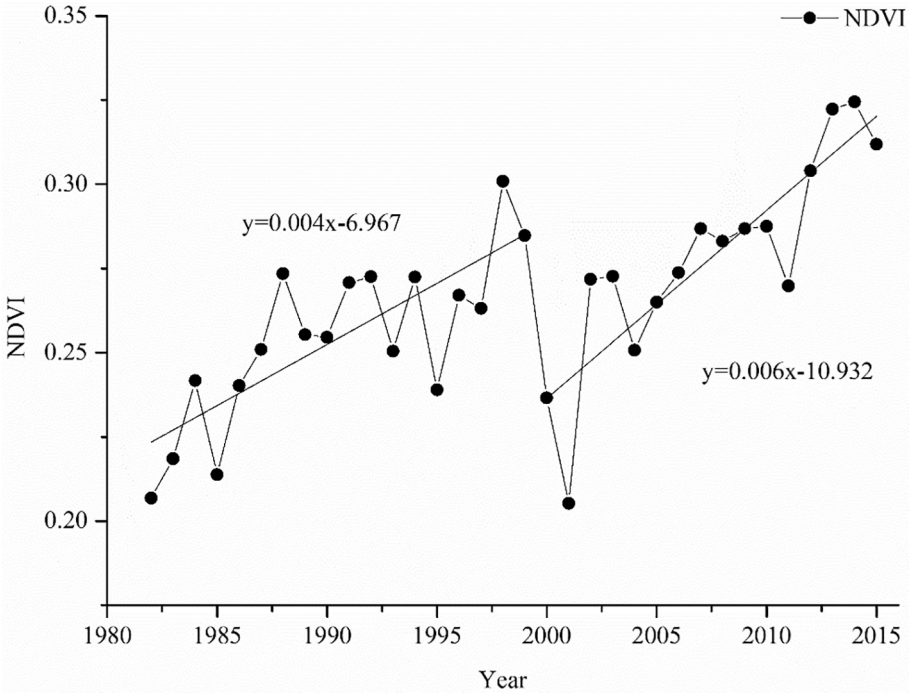

Fig. 3. The change in NDVI from 1982 to 2015.

2015 (Fig. 6 a). The annual average temperature increased from 5.66 °C in 1984 to 8.82 °C in 1999. The temperature change was divided into two periods (i.e., 1982–1996 and 1997–2015) based on the cumulative departure curve (Fig. 6b). During the first period (i.e., 1982–1996), the temperature remained low, with a range of 5.66–7.66 °C and an average annual temperature of 6.84 °C. The annual temperature departure was in the range of −0.25 to 0.01, with an average of −0.09. There were almost negative departures in average annual temperature during this period, and the accumulative departure displayed an obvious decline. Compared to the previous period, the second period (i.e., 1997–2015) had a higher temperature range of 7.21 to 8.81 °C, with an average value of 8.12 °C. During this period, the departure was in the range of −0.04 to 0.16, with an average of 0.07. The averages of temperature and departure in the second period increased by 1.28 and 0.16 °C, respectively, relative to those in the first period. In addition, the accumulative departure presented an increasing trend.

The temporal changes in annual precipitation and its cumulative departure curve from 1982 to 2015 were as follows (Fig. 7). The annual precipitation from 1982 to 2015 fluctuated significantly. The minimum and maximum values for this period were 237.45 mm in 2000 and 543.66 mm in 2012, respectively, with an average of 373.23 mm (Fig. 7a). In contrast, there was no obvious change in annual or CDM

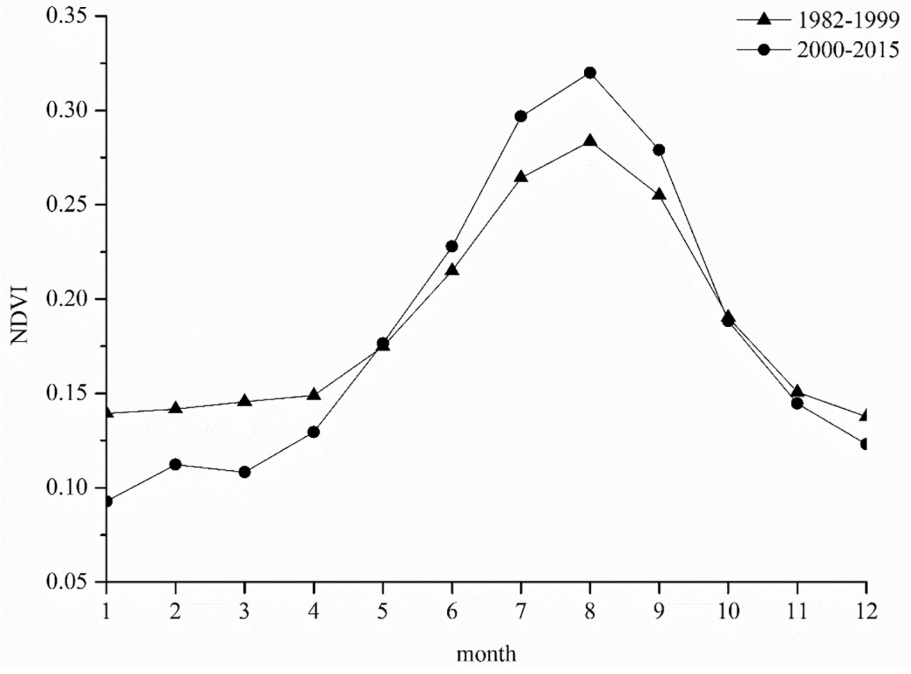

Fig. 4. Intra-annual NDVI changes during the two periods.

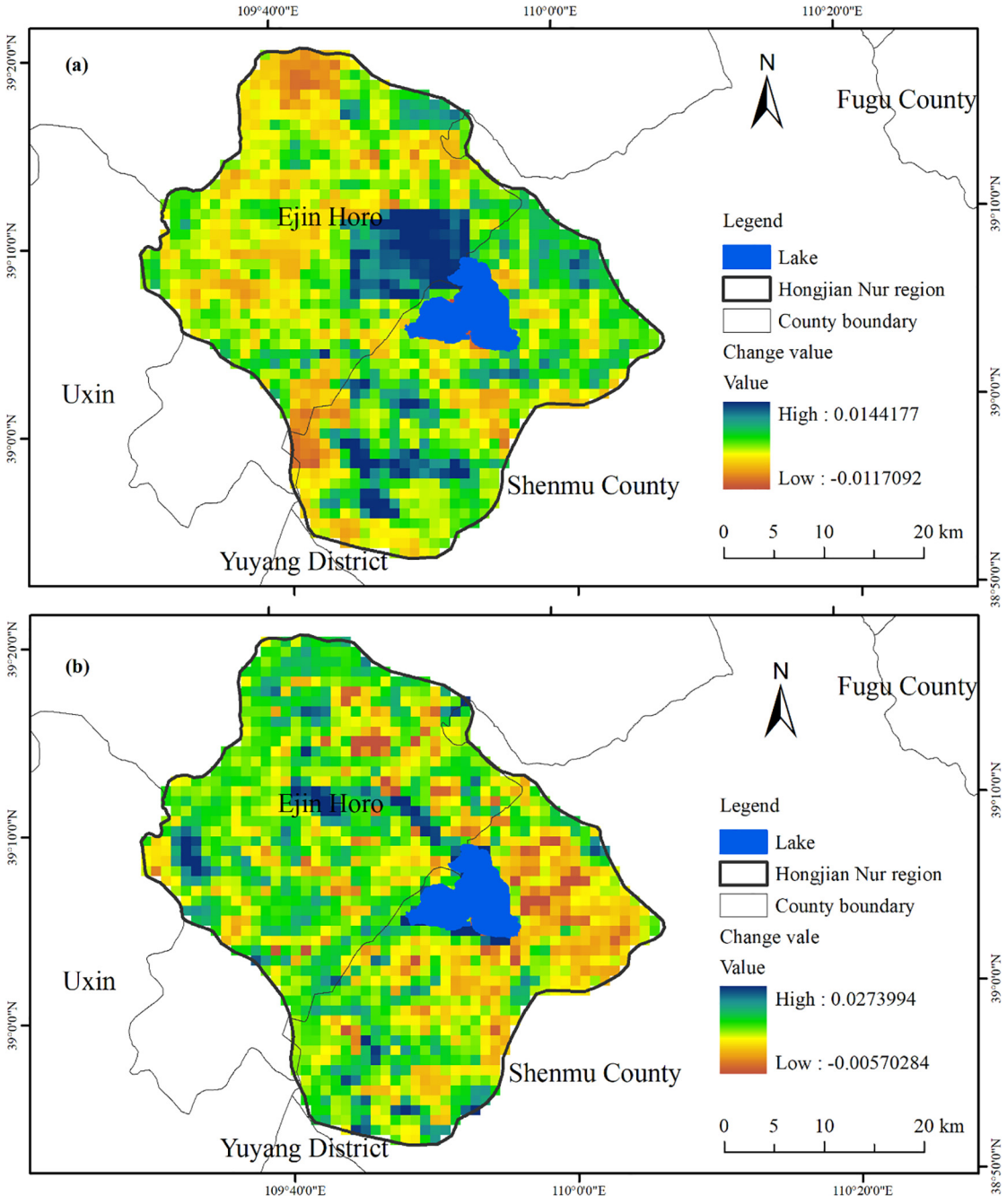

Fig. 5. The spatial distribution of NDVI changes in the HJN region: (a) changes from 1982 to 2015, (b) changes from 2000 to 2015.

Table 7
Wetland area and the NDVI of surrounding vegetation from 1995 to 2015.

	Change (%)				
	1995	2000	2005	2010	2015
The area of wetland	−10.41	−21.52	−25.45	−28.87	−41.18
NDVI	−6.16	−7.07	4.06	12.92	22.48

precipitation (Fig. 7b).

The area of wetlands in the HJN region showed a decreasing trend from 1976 to 2015 (Table 4), and the lake area exhibited a rapid decline starting in 1995. The changes in temperature were divided into two periods. During the first period (i.e., 1982–1996), the temperature increased slowly, with an average annual temperature of 6.84 °C; during the second period (i.e., 1997–2015), the temperature continued to increase, and the average annual temperature was 8.12 °C (Fig. 6). There was no obviously change in precipitation during this period (Fig. 7). In the past three decades, the temperature in the area has increased, and the change in precipitation has been less pronounced. This pattern has resulted in increased evaporation, potentially contributing to the reduction in wetland area.

The relationships between NDVI and climatic factors were analyzed (Table 8). During both 1982–2015 and 1982–1999, there was a positive correlation between NDVI and average annual temperature. However, during 2000–2015, NDVI and average annual temperature were negatively correlated. NDVI and temperature were significantly and positively correlated in spring and autumn, with a higher correlation coefficient in autumn. The correlation coefficients of the previous season were smaller than that of the current season in each period (i.e.,

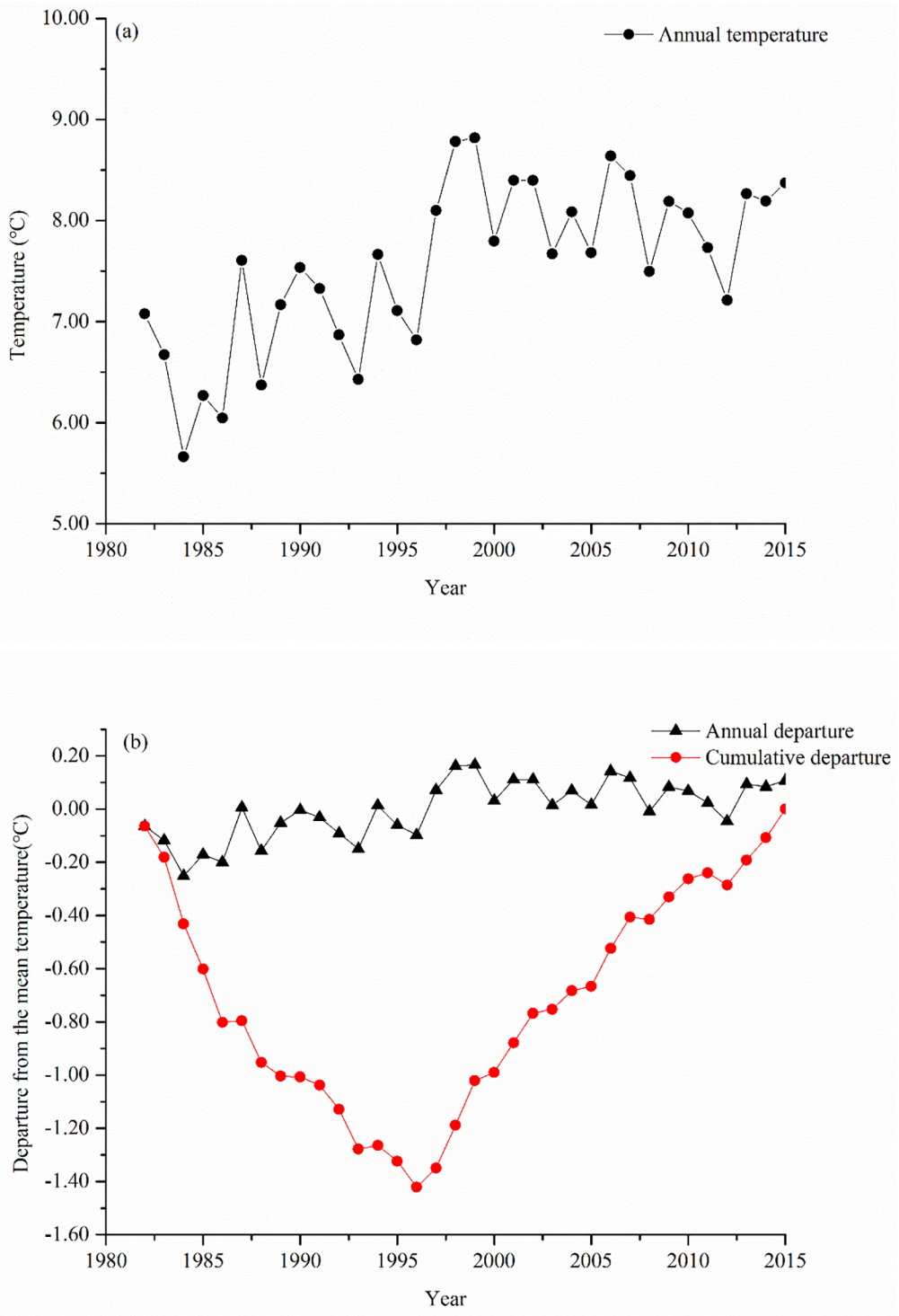

Fig. 6. The change in temperature from 1982 to 2015: (a) annual temperature change, (b) changes in annual and cumulative departure from the mean temperature from 1982 to 2015.

1982–2015, 1982–1999 and 2000–2015). The increase in the correlation coefficient from that of the previous season was greater for spring than for autumn. The correlation between NDVI and temperature in summer was similar to the correlation between NDVI and temperature throughout the entire year, and the correlation coefficient was the smallest except for winter. The increase in annual temperature contributed to the increase in vegetation in the HJN region from 1982 to 1999. However, after 1999, the increase in annual temperature has had an inhibitory effect on vegetation growth. The temperature in autumn contributed the most to the growth of vegetation within a year, followed by spring temperature; in contrast, the temperature in summer had less of an impact on vegetation growth. As seen in Table 8, there was a positive correlation between NDVI and annual precipitation. NDVI had a positive correlation with precipitation in all seasons except for winter, and the correlation coefficient was the highest in autumn. The correlation between summer precipitation and NDVI was weaker for 2000–2015 than for 1982–1999. These results suggest that precipitation in autumn affected on vegetation growth and that the impact

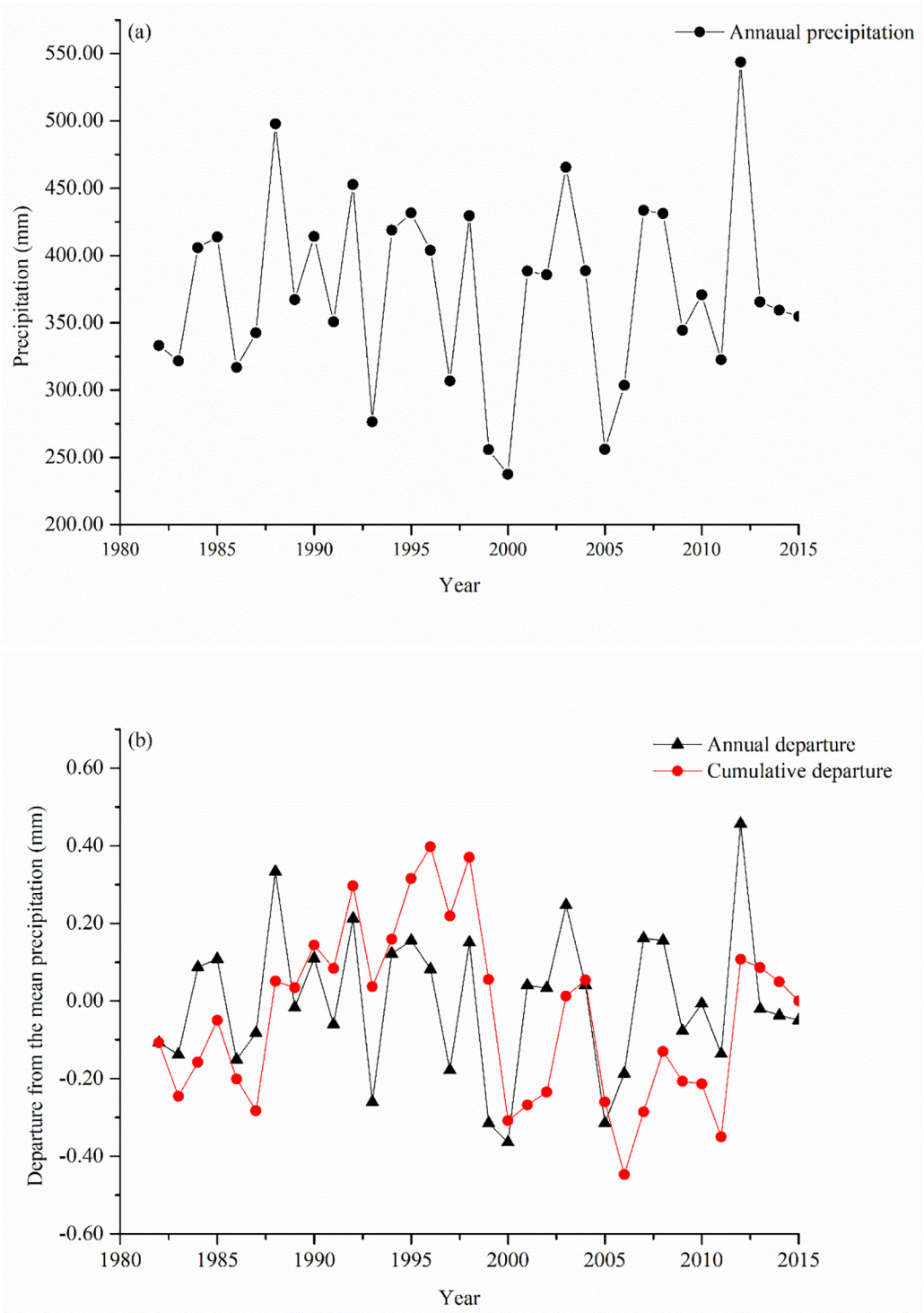

Fig. 7. The change in precipitation from 1982 to 2015: (a) annual precipitation change, (b) changes in annual and cumulative departure from the mean precipitation from 1982 and 2015.

of summer precipitation was small, especially after 2000. The lagging response time of NDVI to temperature or precipitation was not pronounced.

4.5. The influence of human activities

The areas converted from wetland were mainly grassland and cultivated land, which had conversion areas of 14.267 km^2 and 9.786 km^2, respectively (Tables 5, 6). As the area of cultivated land increased, water consumption due to irrigation increased. It can be seen from the remote sensing images in Fig. 8 that the river channels of the Zhasak River and Ronggaitu River, which are the main water sources supplying the wetland areas, gradually narrowed over time; after the completion of the downstream reservoir in 2006, the river channel below the irrigation reservoirs gradually disappeared.

As the population increased, the area of artificial surface expanded. The populations of Shenmu County and Ejin Horo have been increasing (Fig. 9). The population of Shenmu County increased from 273,969 in

Table 8
The correlations between vegetation and the seasonal temperature and precipitation.

		Vegetation								
		Spring	Previous season	Summer	Previous season	Autumn	Previous season	Winter	Previous season	Year
Temperature	1982–2015	0.433**	0.242**	0.053**	0.414**	0.646**	−0.002**	−0.012**	−0.022**	0.029**
	1982–1999	0.278**	0.262**	0.127**	0.416**	0.628**	0.045**	−0.068**	−0.053**	0.076**
	2000–2015	0.660**	0.302**	−0.090**	0.405**	0.670**	−0.047**	0.172**	0.07**	−0.014**
Precipitation	1982–2015	0.262**	0.090**	0.104**	0.169**	0.454**	−0.300**	−0.149**	0.016**	0.079**
	1982–1999	0.178**	0.220**	0.252**	0.175**	0.444**	−0.317**	0.229**	−0.033**	0.030**
	2000–2015	0.332**	0.034**	0.039**	0.199**	0.470**	−0.298**	−0.019**	0.156**	0.135**

Note: The significance level representing $p < 0.01$ was indicated using ** in the upper-right of the Pearson correlation coefficient.

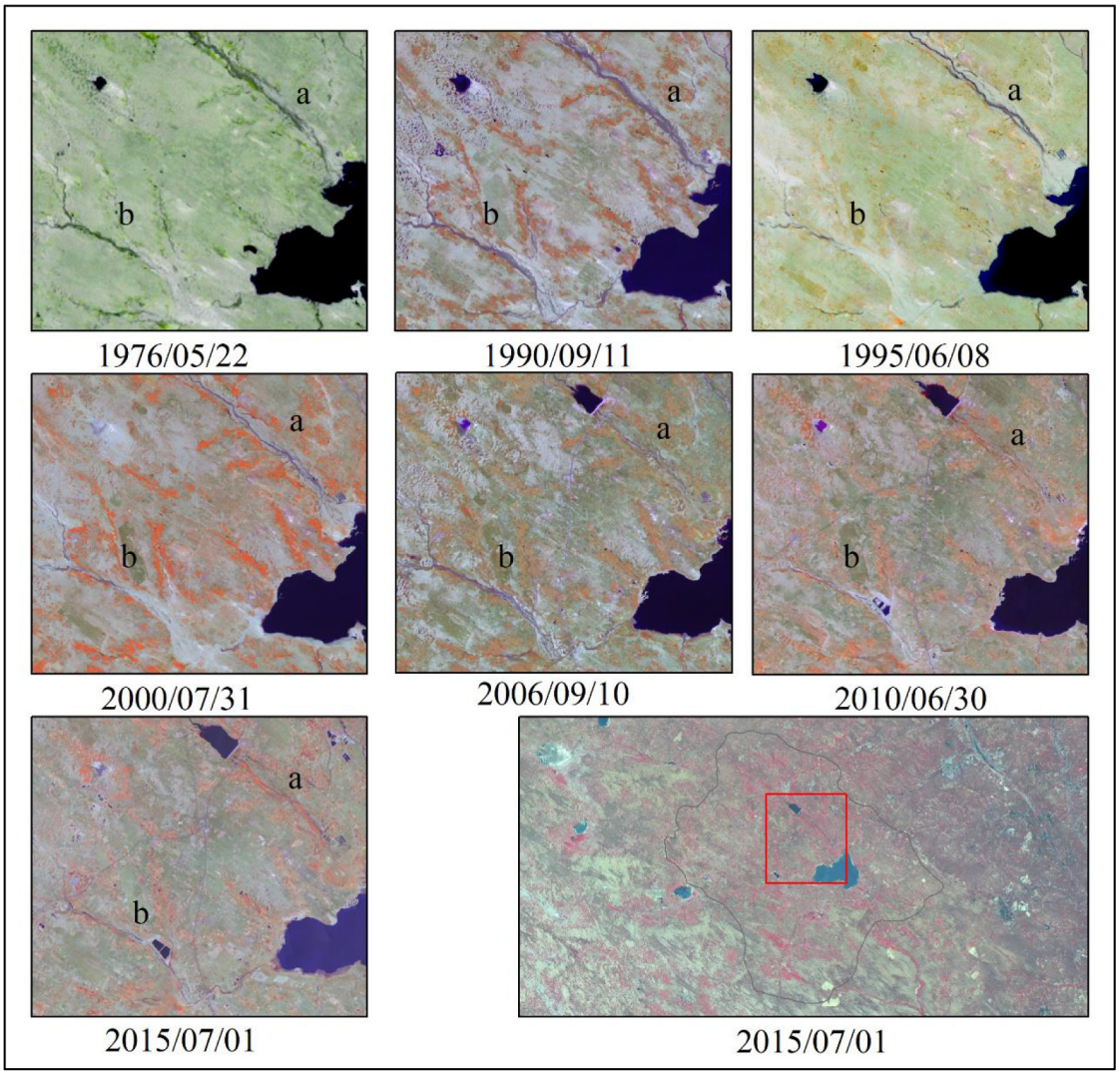

Fig. 8. Changes of Zhasak (a) and Ronggaitu Rivers (b) from 1982 to 2015.

1986 to 173,699 in 2015; the smaller population of Ejin Horo increased from 127,728 to 173,699 over this period. Correspondingly, the area of coal mining has increased extensively in the region since 1995 (Table 4). The resulting domestic and industrial waters use has negative impacts on the wetlands in the region.

Agricultural irrigation and artificial surface development may not fully explain the continuous decrease in wetland area. Water consumption for vegetation in restoration projects cannot be ignored. From 1976 to 2015, the areas of both woodland and sparse vegetation showed increasing trends (Table 4), and the corresponding NDVI values exhibited similar trends (Fig. 10a, c). The increase of woodland area was mainly from the conversion of grassland, and the decrease in sparse vegetation was mainly due to its conversion into grassland (Tables 5, 6). Although the area of grassland decreased, its NDVI value increased (Fig. 10b), which indicated improved grassland growth. Under the influences of rising temperature and stable annual precipitation, ecological engineering projects have increased the areas of woodland and sparse vegetation, improving their growth status. Vegetation restoration projects in desert areas require large amounts of water, which leads to reductions in wetland area.

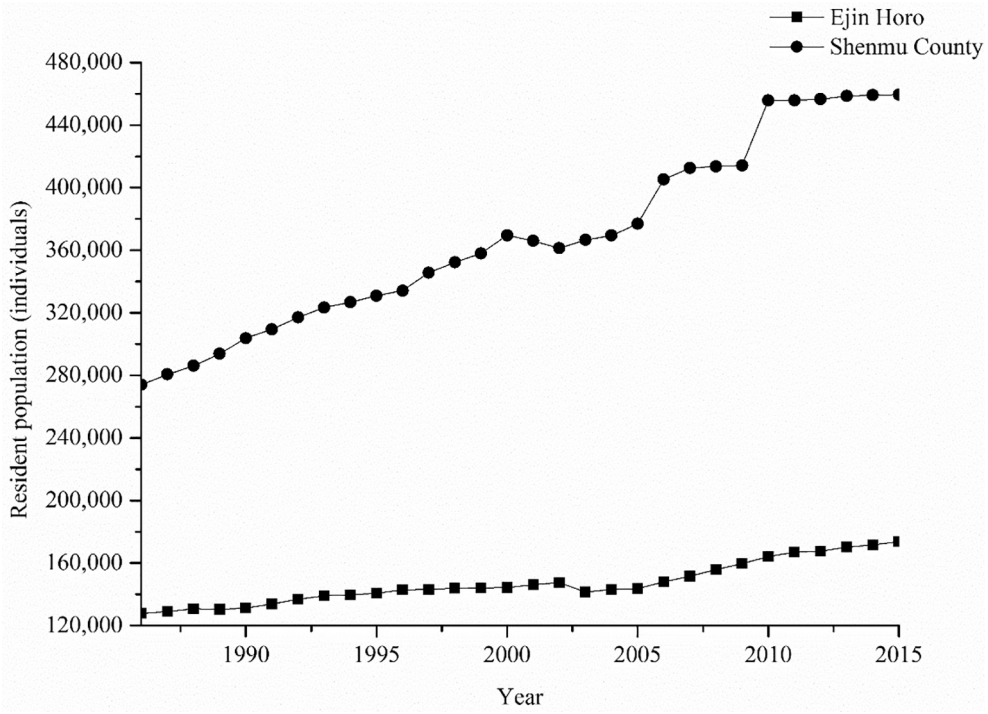

Fig. 9. Population sizes of Ejin Horo and Shenmu County from 1986 to 2015.

5. Discussion

Over the past forty years, the area of wetlands, especially the lake area, in the HJN region has continuously decreased. Our results are consistent with the results of previous studies (Li et al., 2009b; Wang et al., 2011; Liu et al., 2015b; Liu and Yue, 2016). In contrast, the areas of woodland and sparse vegetation in the HJN region have been increasing, and the overall growth condition of the vegetation has improved, especially since 2000. Similar findings have been reported previously (Li et al., 2010; Liu et al., 2017).

The above results mainly reflect the influences of climatic and human factors. The precipitation in the HJN region is low, and the temperature is continuing to rise, resulting in extensive evaporation in the area. This is one of the reasons for the decrease in wetland area. Climatic factors did not appear to contribute greatly to the observed increase in vegetation; however, after 2000, temperature had an inhibitory effect on vegetation growth. Similarly, previous studies have reported that the HJN region has entered an arid climate state, that climate change is one of the reasons for the reductions in wetland areas and that the improvement in vegetation condition is mainly due to by human activities (Li et al., 2010; Luo et al., 2012).

The impact of human activities on the wetland areas of the HJN region is mainly the result of agricultural irrigation, artificial surface expansion and ecological water use. As the population continues to increase, land reclamation activities in the region are becoming more frequent. With the implementation of the “Western Development” policy in China, the area of coal mining has increased extensively in the region, resulting in ground subsidence and the structural destruction of underground aquifers, thus reducing the area of wetlands (Tao et al., 2015). However, human activities such as vegetation restoration play positive roles. Since 1978, the government has implemented a series of ecological and environmental protection restoration projects. These projects have promoted the restoration of vegetation in the HJN region (Jia et al., 2014; Liu et al., 2014). However, this region belongs to a relatively closed inland area, and the groundwater also belongs to a closed and independent sub-region. All water resources extracted are consumed in the region (Li et al., 2009a). Along with the harsh climatic conditions, water allocated to ecological construction has contributed to the reduction of wetlands in the region. Due to the unique geographical environment, increases in agricultural irrigation, vegetation water, and industrial and domestic water consumption directly affect the amount of water entering the wetlands; thus, wetland areas have decreased (Yang et al., 2014). The Zhasak River and the Ronggaitu River are the main water sources that supply the wetlands in the HJN region. From 1997 to 2004, the government built a number of small irrigation reservoirs on the upper reaches of these two rivers (Li et al., 2009a). As the river water is intercepted, less water flows into the HJN region.

The results of this study demonstrated that while the area of wetland area has been reduced, the vegetation condition has improved, especially since 2000. Climate change is only one of the factors causing changes in wetland area, and this study concludes that vegetation restoration may have a negative impact on wetland areas. The main methods of restoration projects include constructing enclosures and establishing ecological forests in the HJN region. Both the initial and middle growth stages of trees require artificial irrigation to meet water demands. Such irrigation in ecological construction requires contributions from rivers and groundwater (Li et al., 2009a).

Although the NDVI used in this study has a higher resolution than other long-term NDVI products, the 1-km resolution is low for the HJN region. In some complex terrains, slope and other topographic factors affect the reflectivity of the vegetation and thus the NDVI values. In addition, the HJN is located in an arid and semiarid area. When the vegetation is sparse, the vegetation tends to degrade. The resulting degraded or exposed spots may affect the reflectivity monitored by remote sensing and thus the NDVI.

This study used remote sensing to monitor changes in wetland area and surrounding land cover as well as NDVI changes in the surrounding vegetation. The degree of the negative impact on the wetland from agricultural irrigation, artificial surface expansion and ecological water use require analysis using other data and methods. Although this study has limitations, it monitored wetland changes in the HJN region and revealed the effects of climate and human activities on wetlands in the area. The findings not only have significance for protecting the valuable

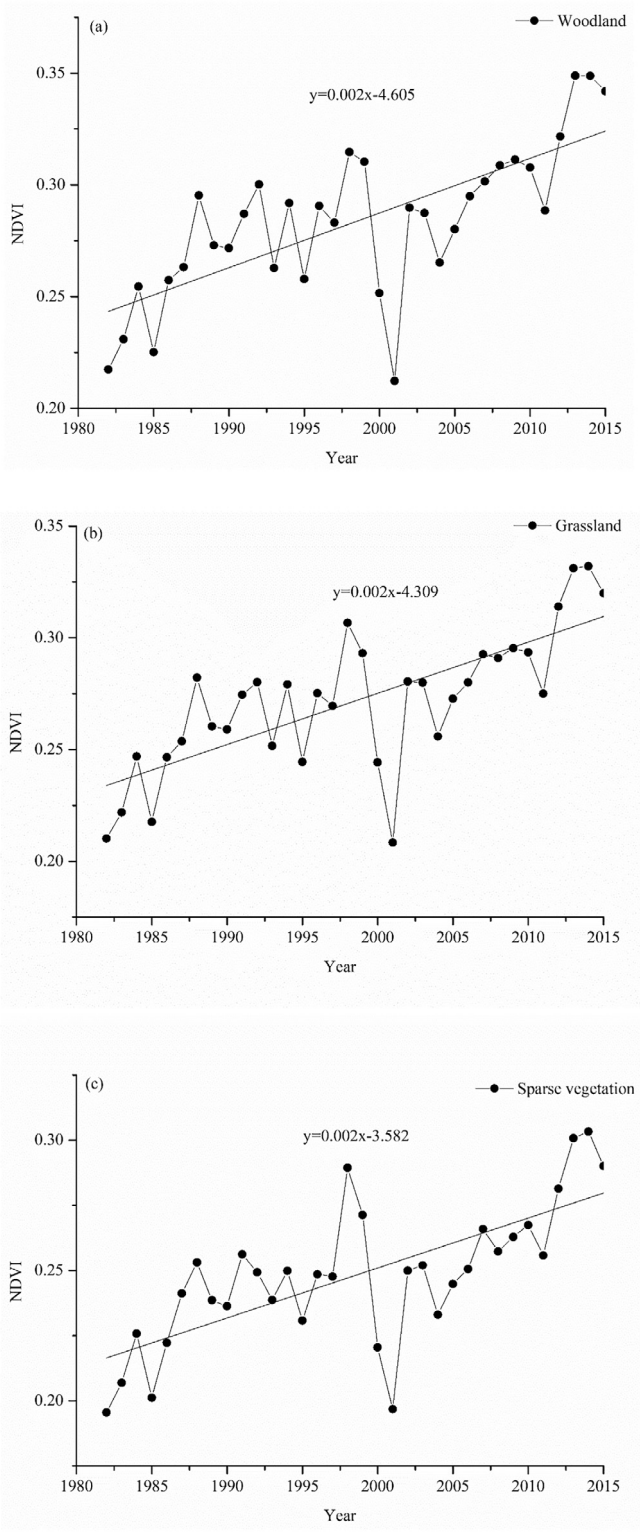

Fig. 10. NDVI changes for different vegetation types from 1982 to 2015.

wetland resources in the HJN region but also suggest that excessive human activities may damage the ecological balance in this arid area and degrade the local ecological environment.

6. Conclusion

The results presented in this study suggest that in the HJN region over the past three decades, the area of wetlands has decreased while the status of surrounding vegetation has continuously improved. Climatic factors partially explain the reduction in wetlands. The impact of human activities on the wetland areas of the HJN region is mainly the result of agricultural irrigation, artificial surface expansion and ecological water use.

The contributions of temperature and precipitation to vegetation growth were small. Ecological restoration projects have had a positive effect on vegetation growth in the region. After decades of efforts, ecological protection measures have contributed to the environmental restoration of the HJN region, slowing the increases in land desertification and grassland degradation. However, vegetation restoration projects may negatively affect the environment, especially wetlands in arid desert areas. Excessive vegetation restoration has affected the wetlands in the region. The local ecological environment should be considered when adopting ecological measures to restore vulnerable habitats and environments in the region.

Acknowledgments

This research was funded by The National Key Research and Development Program of China (grant number 2016YFC0500806), the China National Key Basic Research Program (grant number 2013CB429901) and the National Natural Science Foundation of China (grant number 41171400).

References

Archer, D.R., Fowler, H.J., 2004. Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications. Hydrol. Earth Syst. Sci. 8, 47–61. https://doi.org/10.5194/hess-8-47-2004.

Deng, Y., Xue, X., Zhang, Z., Shen, B., Sun, C., 2014. Assessment and countermeasures for ecological and environmental quality of Hongjiannao. Environ. Sci. Manage. 39, 23–25.

Fensham, R.J., Silcock, J.L., Kerezsy, A., Ponder, W., 2011. Four desert waters: setting arid zone wetland conservation priorities through understanding patterns of endemism. Biol. Conserv. 144, 2459–2467. https://doi.org/10.1016/j.biocon.2011.06.024.

Fu, B., Burgher, I., 2015. Riparian vegetation NDVI dynamics and its relationship with climate, surface water and groundwater. J. Arid Environ. 113, 59–68. https://doi.org/10.1016/j.jaridenv.2014.09.010.

Glenn, E.P., Mexicano, L., Garcia-Hernandez, J., Nagler, P.L., Gomez-Sapiens, M.M., Tang, D., Lomeli, M.A., Ramirez-Hernandez, J., Zamora-Arroyo, F., 2013. Evapotranspiration and water balance of an anthropogenic coastal desert wetland: responses to fire, inflows and salinities. Ecol. Eng. 59, 176–184. https://doi.org/10.1016/j.ecoleng.2012.06.043.

Guay, K.C., Beck, P., Berner, L.T., Goetz, S.J., Baccini, A., Buermann, W., 2014. Vegetation productivity patterns at high northern latitudes: a multi-sensor satellite data assessment. Glob. Change Biol. 20, 3147–3158. https://doi.org/10.1111/gcb.12647.

Halabisky, M., Moskal, L.M., Gillespie, A., Hannam, M., 2016. Reconstructing semi-arid wetland surface water dynamics through spectral mixture analysis of a time series of Landsat satellite images (1984–2011). Remote Sens. Environ. 177, 171–183. https://doi.org/10.1016/j.rse.2016.02.040.

Han, X., Chen, X., Feng, L., 2014. Four decades of winter wetland changes in Poyang Lake based on Landsat observations between 1973 and 2013. Remote Sens. Environ. 156, 426–437. https://doi.org/10.1016/j.rse.2014.10.003.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25, 1965–1978. https://doi.org/10.1002/joc.1276.

Holben, B.N., 1986. Characteristics of maximum-value composite images from temporal AVHRR data. Int. J. Remote Sens. 7, 1417–1434. https://doi.org/10.1080/01431168608948945.

Hulet, A., Roundy, B.A., Petersen, S.L., Jensen, R.R., Bunting, S.C., 2014. An object-based image analysis of pinyon and juniper woodlands treated to reduce fuels. Environ. Manage. 53, 660–671. https://doi.org/10.1007/s00267-013-0227-1.

Hutchinson, M.F., 1995. Interpolating mean rainfall using thin plate smoothing splines. Int. J. Geogr. Inf. Syst. 9, 385–403.

Hutchinson, M.F., Xu, T., 2013. ANUSPLIN.

Jia, X., Fu, B., Feng, X., Hou, G., Liu, Y., Wang, X., 2014. The tradeoff and synergy between ecosystem services in the Grain-for-Green areas in Northern Shaanxi, China. Ecol. Ind. 43, 103–111. https://doi.org/10.1016/j.ecolind.2014.02.028.

Jiang, X., Liu, X., Huang, F., Jiang, H., Cao, W., Zhu, Y., 2010. Comparison of spatial interpolation methods for daily meteorological elements. Chin. J. Appl. Ecol. 21, 624–630.

Li, S., Chen, S., Zhang, J., 2009b. Environmental changes analysis of Hongjiannao Lake during recent fifty years. Resourc. Environ. 10, 178–183.

Li, D., Zhou, J., Wang, Z., 2009a. Effect of human activities and climate change on the water surface area of Hongjiannao Lake. J. Glaciol. Geocryol. 31, 1110–1115.
Li, D., He, H., Liu, A., 2010. Impact of human activities and climate change on vegetation around Hongjian Nur Lake in Northwesttern China. J. Desert Res. 30, 831–836.
Liu, D., Chen, Y., Cai, W., Dong, W., Xiao, J., Chen, J., Zhang, H., Xia, J., Yuan, W., 2014. The contribution of China's Grain to Green Program to carbon sequestration. Landscape Ecol. 29, 1675–1688. https://doi.org/10.1007/s10980-014-0081-4.
Liu, P., Gao, Y., Lyv, L., Wang, H., 2015a. Characteristics of soil properties to land use/cover change in Hongjiannao Watershed. Environ. Sci. Technol. 38, 7–12. https://doi.org/10.3969/j.issn.1003-6504.2015.09.002.
Liu, S., Kang, W., Wang, T., 2016. Drought variability in Inner Mongolia of northern China during 1960–2013 based on standardized precipitation evapotranspiration index. Environ. Earth Sci. 75, 1–14. https://doi.org/10.1007/s12665-015-4996-0.
Liu, B., Tang, Z., Dong, S., Wang, L., Liu, D., 2018. Vegetation recovery and groundwater pollution control of coal gangue field in a semi-arid area for a field application. Int. Biodeterior. Biodegrad. 128, 134–140. https://doi.org/10.1016/j.ibiod.2017.01.032.
Liu, Y., Yue, H., 2016. Analysis of Hongjiannao Lake Area Based on SMMI. Sci. Technol. Eng. 16, 122–127.
Liu, Y., Wu, L., Yue, H., 2015b. Monitoring of Hongjiannao Lake Area Based on Landsat and HJ Imageries. Geogr. Geo-Inf. Sci. 31, 60–64.
Liu, Y., Yue, H., Wang, T., 2017. Dynamic change of land use/cover and spatio-temporal evolution of landscape pattern in Hongjiannao Region during 1990–2015. Bull. Soil Water Conserv. 37, 224–230.
Luo, G., Wang, W., Ge, L., Wang, R., 2012. Water ecology status and protection measures for Hongjiannao Basin. J. Hydroecol. 33, 147–152. https://doi.org/10.15928/j.1674-3075.2012.02.020.
Maleki, S., Soffianian, A.R., Soltani Koupaei, S., Saatchi, S., Pourmanafi, S., Sheikholeslam, F., 2016. Habitat mapping as a tool for water birds conservation planning in an arid zone wetland: the case study Hamun wetland. Ecol. Eng. 95, 594–603. https://doi.org/10.1016/j.ecoleng.2016.06.115.
Mandal, S., Srivastav, R.K., Simonovic, S.P., 2016. Use of beta regression for statistical downscaling of precipitation in the Campbell River basin, British Columbia, Canada. J. Hydrol. 538, 49–62. https://doi.org/10.1016/j.jhydrol.2016.04.009.
Mao, D., Wang, Z., Luo, L., Ren, C., 2012. Integrating AVHRR and MODIS data to monitor NDVI changes and their relationships with climatic parameters in Northeast China. Int. J. Appl. Earth Observ. Geoinf. 18, 528–536. https://doi.org/10.1016/j.jag.2011.10.007.
Moreno-Mateos, D., Pedrocchi, C., Comín, F.A., 2010. Effects of wetland construction on water quality in a semi-arid catchment degraded by intensive agricultural use. Ecol. Eng. 36, 631–639. https://doi.org/10.1016/j.ecoleng.2009.02.003.
Qian, D., Yan, C., Xing, Z., Xiu, L., 2017. Monitoring coal mine changes and their impact on landscape patterns in an alpine region: a case study of the Muli coal mine in the Qinghai-Tibet Plateau. Environ. Monit. Assess. 189. https://doi.org/10.1007/s10661-017-6284-9.
Stow, D., Daeschner, S., Hope, A., Douglas, D., Petersen, A., Myneni, R., Oechel, W., 2003. Variability of the seasonally integrated normalized difference vegetation index across the North Slope of Alaska in the 1990s. Int. J. Remote Sens. 24, 1111–1117. https://doi.org/10.1080/0143116021000020144.
Sultan, D., Song, Y., Marina, J., 2004. Influence of groundwater level change on vegetation coverage and their spatial variation in arid regions. J. Geog. Sci. 14, 323–329.
Tao, S., Fang, J., Zhao, X., Zhao, S., Shen, H., Hu, H., Tang, Z., Wang, Z., Guo, Q., 2015. Rapid loss of lakes on the Mongolian Plateau. Proc. Natl. Acad. Sci. 112, 2281–2286. https://doi.org/10.1073/pnas.1411748112.
Trenholm, R., Haider, W., Lantz, V., Knowler, D., Haegeli, P., 2017. Landowner preferences for wetlands conservation programs in two Southern Ontario watersheds. J. Environ. Manage. 200, 6–21. https://doi.org/10.1016/j.jenvman.2017.05.055.
Voltersen, M., Berger, C., Hese, S., Schmullius, C., 2014. Remote sensing of environment object-based land cover mapping and comprehensive feature calculation for an automated derivation of urban structure types at block level. Remote Sens. Environ. 154, 192–201. https://doi.org/10.1016/j.rse.2014.08.024.
Wang, J., Qu, J., Zhang, W., 2011. Extraction and monitoring of Hongjiannao Lake Area in Mu us sandy land based on mixed pixel decomposition of remote sensing data. J. Desert Res. 31, 558–562.
Xiang, Y., Wei, A., Song, J., Huang, A., Gao, H., Zhang, Y., Zheng, X., 2016. Coupling relationship between population fluctuation of relict gulls and habitat factors in Hongjian Nur Wetland. J. Shandong Agric. Univ. 47, 186–193. https://doi.org/10.3969/j.issn.1000-2324.2016.02.006.
Xin, Z., Xu, J., Zheng, W., 2008. Spatiotemporal variations of vegetation cover on the Chinese Loess Plateau (1981–2006): impacts of climate changes and human activities. Sci. China, Ser. D Earth Sci. 51, 67–78. https://doi.org/10.1007/s11430-007-0137-2.
Xu, Y., Yang, J., Chen, Y., 2016. NDVI-based vegetation responses to climate change in an arid area of China. Theor. Appl. Climatol. 126, 213–222. https://doi.org/10.1007/s00704-015-1572-1.
Yan, G., Lou, H., Liang, K., Zhang, Z., 2016. Dynamics and driving forces of Bojiang Lake area in Erdos Larus Relictus National Nature Reserve, China. Quaternary Int. 1–12. https://doi.org/10.1016/j.quaint.2016.12.034.
Yang, L., Huang, Q., Wu, J., Jia, Z., 2014. Influence factors and prediction on area change of lake Hongjiannao. J. Arid Resour. Environ. 28, 74–78. https://doi.org/10.13448/j.cnki.jalre.2014.03.035.
Yu, X., Liu, X., Wang, Y., 2016. Ecological risk assessment of heavy metals in the surface sediment of Hongjiannao Lake, Shaanxi Province, China. J. Earth Environ. 7, 173–182. https://doi.org/10.7515/JEE201602007.
Zhang, H., Liu, P., Li, X., 2011. Land use dynamic change of Hongjiannao Watershed in Northern Shaanxi Province. Environ. Sci. Technol. 34, 180–183. https://doi.org/10.3969/j.issn.1003-6504.2011.03.041.
Zhang, Q., Sun, R., Jiang, G., Xu, Z., Liu, S., 2016. Carbon and energy flux from a Phragmites australis wetland in Zhangye oasis-desert area, China. Agric. For. Meteorol. 230–231, 45–57. https://doi.org/10.1016/j.agrformet.2016.02.019.
Zhang, L., Wu, B., Li, X., Xing, Q., 2014. Classification system of China land cover for carbon budget. Acta Ecol. Sin. 34, 7158–7166. https://doi.org/10.5846/stxb201310102431.
Zhang, G., Zhang, Y., Dong, J., Xiao, X., 2013. Green-up dates in the Tibetan Plateau have continuously advanced from 1982 to 2011. Proc. Natl. Acad. Sci. 110, 4309–4314. https://doi.org/10.1073/pnas.1210423110.
Zhao, N., Ma, C., Yang, Y., 2016. Water quality variation of Lake Hongjiannao and its driving force analysis from 1973 to 2013. J. Lake Sci. 28, 982–993.
Zhu, L., Gong, H., Dai, Z., Xu, T., Su, X., 2015. An integrated assessment of the impact of precipitation and groundwater on vegetation growth in arid and semiarid areas. Environ. Earth Sci. 74, 5009–5021. https://doi.org/10.1007/s12665-015-4513-5.